# 24

# Flow Metrology: Standards, Calibrations, and Traceabilities

As increased concerns for improved fluid flow rate measurement drive the fluid metering community—meter manufacturers and users alike—to search for increased flow measurement accuracy and precision, better verification and documentation are needed to substantiate fluid meter performance. These concerns affect both domestic and international market places; they permeate instrumentation and control technologies—aerospace, chemical processes, automotive, bioengineering, etc. They involve public health and safety, and they impact our national defense. These concerns are based upon the rising value of fluid resources and products and the importance of critical material accountability. These values directly impact the increased accuracy needs of fluid buyers and sellers in custody transfers. These concerns impact the designers and operators of chemical process systems where increased control and productivity optimization depend critically upon measurement precision. Public health and safety depend upon advancing the quality of numerous pollutant measurements—both liquid and gaseous. The performance testing of engines—both automotive and aircraft—are critically based upon accurate fuel measurements—both liquid and oxidizer streams. For all these reasons, flow metrology, its standards, its calibrations, and its traceabilities need to be understood, well established, and properly used to document and validate fluid quantity and flow rate measurements.

Fluid flow rate measurements are established differently from counterparts in length and mass measurement systems because these have the benefits of "identity" standards. For rate measurement systems, the metrology is based upon "derived standards." These use facilities and transfer standards that are designed, built, characterized, and used to constitute basic measurement capabilities and quantify performance (accuracy and precision). Because "identity standards" do not exist for flow measurements, facsimiles or equivalents must be concocted and used to quantify the systematic errors that might exist between or among measurement facilities for fluid flow rate or air speed, etc. This is the purpose of this chapter: to describe the ways that flow measurement facilities can be characterized and how traceability of these facilities can be established. Examples of the performance assessment for flow rate measurement facilities are given using typical values prevailing at the National Institute of Standards and Technology (NIST, formerly the National Bureau of Standards).

## Standards

Fluid flow rate standards could be significantly simplified if the fundamental bases of these measurements were as simple as those for mass, length, and so on.

These systems of measurement are based upon discrete standards[1] or artifacts. For examples, the platinum kilogram known as "K-20" is the ultimate artifact to provide the fundamental basis for mass measurement in the U.S., and the platinum meter bar (or its modern-day wavelength equivalent) is the ultimate artifact to provide the fundamental basis for length measurement. These artifacts can be considered "identity" standards.

## Identity Standards

These mass and length artifacts can be considered "identity" standards because under the appropriate conditions of use they define the basic quantity in their respective measurement systems. However, for flow rate measurements of fluids, i.e., liquids or gases, there does not exist an identity standard such as a gallon per minute, a liter per second, or a kilogram per hour. To supply the fundamental basis upon which to establish a flow measurement system, a "derived" standard is needed.

## Derived Standards for Flow

For fluid flow rate measurements, as needed to form the basis of a national reference system, calibration facilities spanning a range of fluid and flow conditions are maintained by NIST for use by industry and others, [Refs. 1-6]. These facilities consist usually of:

(1) a source of flow, generally a compressor or a pump, and a supply of the fluid with appropriate auxiliary equipment such as a regulated, pressurized tank of gas or a reservoir of liquid;

(2) a test section into which the meter and its adjacent piping can be installed so that the flow and fluid conditions into it duplicate those expected where the meter will actually be used; and

(3) a flow determination system having a specified level of performance and appropriate proof of this to specify and assure the desired metering performance of the devices in question. Calibration systems are generally categorized according to the type of flow determination scheme used.

## Flow Determination Systems

The heart of the fluid flowmeter calibration facility is the flow determination system, [Refs. 1-6]. This generally uses a timed collection of the fluid that flows through the meter being calibrated. The amount of fluid collected is determined by gravimetric or volumetric techniques. This collected fluid is converted to flow rate using the collection time; the volumetric flow rate through the meter can be determined via conservation of mass principles using the pertinent thermodynamic properties measured at the meter. This system can be made to perform at a high level of performance to determine the bulk flow rate of the fluid.

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1 The term "standard" has many meanings. It is used to refer to "paper" standards, which are documents; it is also used to refer to reference facilities and equipment; it is also used to refer to the specific materials needed to transfer measurement quality from or between facilities. These specific materials are referred to in what follows as "artifacts."

## Levels of Performance

Measurement systems can be characterized through their accuracy and precision. These terms are briefly defined as follows:

*Accuracy*—The degree, generally expressed as a percent, to which a measured result approximates the true value of the quantity being measured.

*Precision*—The degree, generally expressed as a percent, to which successive determinations of the same quantity duplicate each other. Precision is sometimes further subdivided into:
"reproducibility," which involves "how closely will successive determinations duplicate each other," or
"repeatability," which involves "how closely can successive determinations be made to duplicate each other" (i.e., when conditions are the same and there is only a short time between measurements).

These characteristics apply to measurements made by flowmeters and to measurements made using calibration facilities, [Refs. 7-11].

## Facility Performance

For fluid flow calibration facilities, the precision can be theoretically evaluated from the appropriate error budget and from the precision of the component measurements that constitute the system. This evaluation technique is often referred to as the propagation of error approach, [Refs. 9-11]. It should be stressed that this approach can lead to serious underestimates of the actual conditions. This is because the physical model for the actual process may not conform to that used for the propagation of errors. Furthermore, difficulty is encountered when facility accuracy is to be quantified, because the true value of the fluid flow rate is not easily obtained. To estimate possible systematic offsets from true value, approximations, generally very conservative, are frequently used. Alternatively, and more preferably, a realistic and highly defensible traceability scheme either should be used or can be generated and then appropriately used to quantify the systematic offset of a calibration facility. This quantification should be done on a continuing basis to assure traceability to national standards.

## Traceability

The concept of measurement traceability is based upon the need to check measurement results. As such, traceability has come to mean many things to many persons. There are a number of definitions for traceability [Ref. 12]. For example, a prevalently used definition for traceability "is to calibrate into a hierarchical scheme of measurements that leads, ultimately, to the national references for the respective measurements." For flow rate measurement systems that are based upon timed gravimetric or volumetric collection schemes, this definition could be implemented by checking, individually, the weighing or volumetric technique in addition to checking the timing device. However, limitations to this type of traceability for fluid flow rate measurement can be that errors can occur in the other components that contribute to the end result. Examples would be the associated temperature, pressure, or humidity measurements that may be influential. Equivalently, the mechanism that starts and stops the timing device can be in error so that even if the timing device itself is accurate and traceable, the timing can be wrong due to faulty activation. Many other errors can affect flow measurement processes.

### Conventional Calibration Procedures

With conventional calibration procedures, a testing laboratory or a meter manufacturer might own and routinely use a master meter technique to assess the flow rate measurement performance of the laboratory with a report on its performance in an NIST facility. The meter would be placed into the respective facility in the laboratory and then calibrated. The relative performance of these calibrations would hopefully compare very favorably and, thereby, document the closeness of agreement between the laboratory's facility and NIST. This procedure, while widely used at the present time, can leave a considerable number of factors affecting measurement completely unassessed.

Traceability might also be established for a flowmeter calibration laboratory in the following manner. If calibrated weights (for example, from a state office of weights and measures) were used to check the scale system and if a timing standard were used to check the lab's timing system, then traceability could be asserted for the weigh-time system. However, the overall ability of the lab to calibrate a flowmeter can be quite incomplete. For such reasons, it is widely believed that more complete assessment of the measurement capabilities of a flow measurement laboratory is preferred. This type of traceability can be established and maintained via flow measurement assurance programs, i.e., flow MAPs.

### Flow Measurement Assurance Programs (MAPs)

In the case of flow MAPs, a procedure is used that is different from conventional calibrations [Refs. 13 and 14]. This involves NIST (or an initiating laboratory) sending a very reliable and well characterized artifact package (i.e., tandem meter arrangements consisting of two meters in series) to the laboratory in question with the request for a calibration of the arrangement according to tightly specified and prearranged conditions [Refs. 15 and 16]. The results, which contain the effects of all the lab's routine calibration procedures, its facilities, its operating conditions, its personnel, and its techniques for calculating final results from raw data, are then sent to NIST. These can be objectively (and informedly) compared to similar results from a number of other labs that have performed the same tests in a "round robin" set of these calibrations. In these comparisons, NIST results are also incorporated as one of the participants. The results show, quantitatively, the agreement (or disagreement) among the participants' results. Algorithms have been developed to handle these results [Refs. 17 and 18]. Figure 24-1 shows a comparison of conventional calibration procedures and those that can occur with MAPs. The comparison shows that the crucial advantages of the MAP program are that: (1) all aspects of the laboratory's measurement processes are checked, and (2) there is a "feedback" and, if necessary, a "follow-up" activity that can make improvements, etc. These follow-up activities can be directed either at the lab's procedures or at its calibration procedures and facilities, depending upon the results obtained from previous rounds of testing.

## Analysis and Results

### Conservation of Mass Equation

Flow calibrations are usually performed using a system that includes a source of flow, the instrument being calibrated, connecting conduits, and a scheme for determining the fluid flow rate. When the calibration is based upon the bulk flow rate, i.e., either volumetric or gravimetric, the scheme for determining the fluid flow is based on conservation of mass considerations, [Refs. 1-4]. When the

calibration is based upon the local fluid velocity, as in the case for air speed calibrations, the scheme for determining fluid velocity is generally a transfer standard such as an accurate Pitot static tube, an anemometer, or a laser Doppler velocimeter (LDV). For each of these schemes, the ideal error budget should be known and maintained so that overall performance levels are as quoted [Refs. 1-3].

Figure 24-2 is a sketch of a calibration arrangement with labelled components. The meter and its downstream piping are considered as a part of the meter and volume a. Depending on the type of calibrator, control surface 4 of volume c may be a moving piston, the stationary end of a tank, etc. Conservation of mass principles applied to an arbitrary, stationary control volume, $V$, which is surrounded by the control surface $S$, can be written:

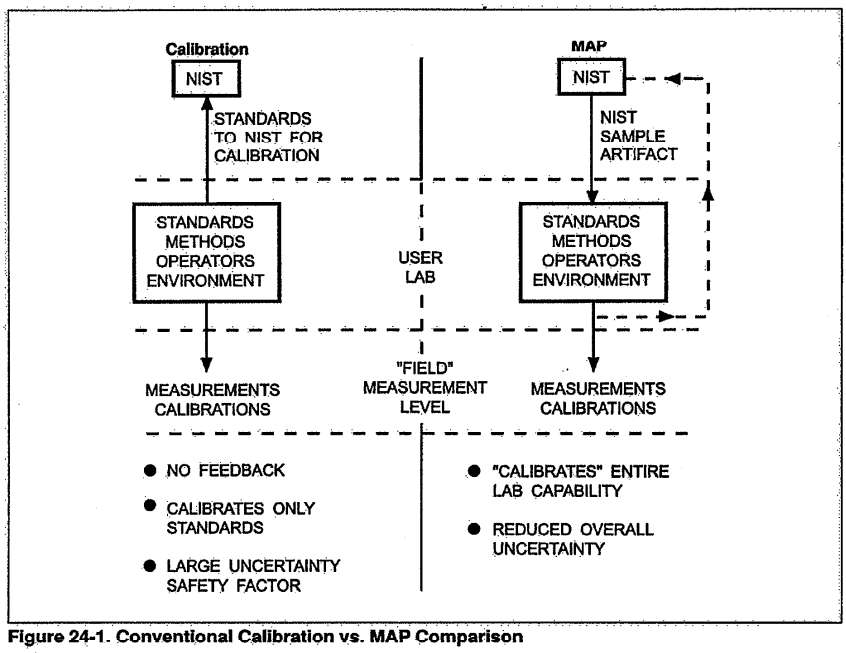


**Figure 24-1. Conventional Calibration vs. MAP Comparison**

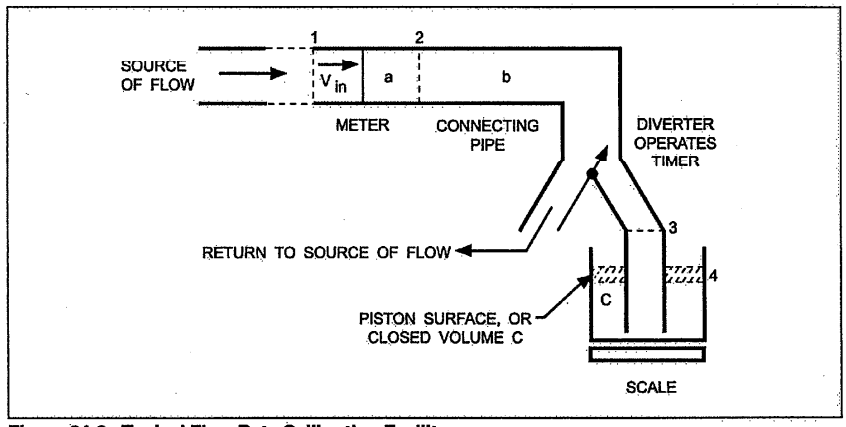


**Figure 24-2. Typical Flow Rate Calibration Facility**

$$0 = \frac{\partial}{\partial t}\int_V \rho dV - \int_S \rho \bar{n} \cdot \bar{v} dS \tag{24-1}$$

where ρ is the fluid density, $\partial/\partial t$ is the partial derivative with time, $V$ is the control volume, which is composed of all the subvolumes in Figure 24-2. The quantity $\bar{v}$ is the vector velocity of the fluid and $\bar{n}dS$ is the vectorial control surface element of area with direction taken inward and normal to the surface. Applications of Equation (24-1) to the control volume and surfaces shown in Figure 24-2 gives:

$$\dot{M} = \int_{S_1} \rho_1 v_{1n} dS_1 = \frac{\partial M_c}{\partial t} + \int_{S_4} \rho_4 v_{4n} + \int_{V_a} \frac{\partial}{\partial t}\rho_a dV_a + \int_{V_b} \frac{\partial}{\partial t}\rho_b dV_b \tag{24-2}$$

where $\dot{M}$ is the mass flow rate through the 1 surface and $\frac{\partial M_c}{\partial t}$ is the rate of fluid mass collected in volume c. Subscripts $n$ refer to vector components normal to the numbered surfaces; integer subscripts refer to surfaces; lettered subscripts refer to volumes.

Performance levels for bulk flow rate calibration facilities can be assessed using the above principles. These principles have been used to produce the quantifications of the uncertainties of the NIST flow facilities, [Refs. 1-4].

## Fluid Meter Calibration Facilities

To attain the improved flow measurement accuracy needed to calibrate fluid meters, a range of techniques are used. These generally consist of systems that are based upon timed collections of the fluid passing through the meter being calibrated. The collected fluid quantities are assessed, using either volumetric or gravimetric methods. These calibration facilities are arranged and used so that the uncertainty of the unit can be determined and quantified as described below.

**An alternative approach to using mobile calibrators or provers to calibrate meters in situ is to use other flowmeters as transfer standards. These should be designed to match, or preferably to exceed, the levels of performance of the installed units. By properly controlling the test conditions and the associated uncertainties, the flow measurement results from the installed units can attain the desired validity or credibility or both.**

Because of the importance of the precision and accuracy levels of fluid quantity and flow rate measurement, calibration facilities are needed frequently to validate results. For these reasons, a range of calibrators and provers are manufactured by several makers of fluid meters. These are either laboratory based or are mobile and used to perform calibration tests in situ on installed flowmeters.

## Uncertainty Assessment

The performance of a calibration facility can be assessed in several ways. Before the facility is designed and built, performance can be assessed on the basis of the operational equation for the facility and the specifications of the component measurements. For example, a static gravimetric facility for measuring liquid volumetric flow rate can operate with the equation:

$$\dot{V} = \frac{M_N}{\rho t} \tag{24-3}$$

where, in compatible units, $\dot{V}$ is the volumetric flow rate, $M_N$ is the net mass of liquid collected (i.e., the difference between the gross mass collected, $M_G$, and the tare mass of the collection tank, $M_T$), ρ is the appropriate liquid density, and $t$ is the collection time. Based upon this model, the uncertainty in the determination of $\dot{V}$ can be specified in terms of the uncertainties in the values of $M_N$, ρ, and $t$. Assessment of the magnitudes of these results can be estimated by several techniques for combining component uncertainties. Two such examples are:

$$\frac{\Delta \dot{V}}{\dot{V}} \le \left[\left(\frac{\Delta M_N}{M_N}\right)^2 + \left(\frac{\Delta \rho}{\rho}\right)^2 + \left(\frac{\Delta t}{t}\right)^2\right]^{1/2} \tag{24-4}$$

and

$$\frac{\Delta \dot{V}}{\dot{V}} \leq \left|\frac{\Delta M_N}{M_N}\right| + \left|\frac{\Delta \rho}{\rho}\right| + \left|\frac{\Delta t}{t}\right| \qquad (24\text{-}5)$$

By inserting values for the precisions (percents of rate, *not* percents of full scale) for the respective components in the right-hand sides of Equations (24-4) and (24-5) one can obtain an initial estimate for the precision that can be expected in the determination of the volumetric flow rate, $\dot{V}$. These determinations are based upon a number of important assumptions such as: (a) Equation (24-3) is the proper model of the process, (b) an adequate data base is used to form the component uncertainties in Equations (24-4) and (24-5), and (c) no other factors are involved. To varying degrees, a number of other factors can be involved, and, for these reasons, further assessments are needed.

After the facility is built, improved assessment of performance is possible, and this should be done in several stages. In the first stage, the components should be checked individually against the respective standards for each respective measurement. These can be considered "static" checks. They could consist of checking weigh systems with mass standards, checking timing and density measuring systems against appropriate standards, and so on.

For liquid flow rate measurement using static gravimetric techniques at NIST-Gaithersburg, the uncertainties (3 standard deviations) for the component measurements have nominal values, as follows:

| Item | Uncertainty (%) |
|---|---|
| Net mass determination | 0.02 |
| Liquid density | 0.02 |
| Collection time | 0.01 |

These can be combined using Equations (24-4) or (24-5) to produce liquid flow rate precision levels of ± 0.03% or ± 0.05%, respectively.

For gas flow rate measurement using piston-volumetric displacement techniques at NIST-Gaithersburg, the uncertainties (3 standard deviations) for the component measurements have nominal values as follows:

| Item | Uncertainty (%) |
|---|---|
| Net mass determination | |
| 1. Volume | 0.04 |
| 2. Density | |
| a. Pressure effects | 0.13 |
| b. Temperature effects | 0.05 |
| Collection time | |
| 1. Device | 0.01 |
| 2. Switching | 0.02 |

These can be combined using Equations (24-4) or (24-5) to produce gas flow rate precision levels of ± 0.15% or ± 0.25%, respectively. It should be noted that these performance levels are those obtained after the respective instruments have been calibrated.

When these static checks of instrument performance give satisfactory results, one should proceed to the next phase of checking. The facility should be operated over its pertinent parameter ranges and data should be obtained for all the measurable quantities under realistic ("dynamic") conditions. This data quantifies the precision of the volumetric flow rate determined "dynamically." These values quantify the left-hand side of Equations (24-4) or (24-5). Additionally,

these data should be compared to that obtained statically for the right-hand sides of Equations (24-4) and (24-5). Satisfactory agreement should be achieved for these precision assessments before the third stage of assessment is started.

The third stage of assessment should be directed at the systematic errors that may be present in the facility's measurement processes. This is properly done by conducting appropriate interlaboratory or "round robin" tests, thereby establishing its traceability. In this way the performance of the laboratory is quantified using its normal, routine materials, procedures, and personnel, and in its environmental conditions. Such quantifications are based upon the test results produced using transfer standards or "artifacts." These artifacts are comprised of flowmeters; the type of flowmeter, its size, the fluid used, and the other test conditions should be selected according to the routine types of flow testing that occur in the laboratory. These artifact meters are tested, i.e., calibrated, according to strictly controlled algorithms as described above. These algorithms are arranged to precisely stipulate all the details of the artifact testing procedures, complete with "go" and "no-go" check points to ensure the validity of the meters and the techniques for analyzing and presenting the data. Done properly and on a continuing basis, the third stage of quantifying flow measurement facility performance provides and maintains realistic traceability for the facility and, in turn, for the measurement products (i.e., calibration data produced by the facility). When this data is properly processed and analyzed to demonstrate that the facility's performance is satisfactory, considerable assurance can be placed in this facility. For this reason, these round robin activities have been named flow MAPs (measurement assurance programs). When these programs include or closely connect to the national reference systems (NIST), strong traceability links are produced.

NIST has initiated a number of round robin flowmeter testing programs as described below. Based upon these tests, NIST uses an estimated systematic uncertainty of ± 0.1% for both its liquid and gas measurement facilities. If this estimated systematic uncertainty is root-sum-squared with the precisions described previously, the total accuracy quotes for liquids and gases would be ± 0.10% and ± 0.18%, respectively. However, because the systematic error is estimated, it is generally preferred to use the more conservative addition method to produce the accuracy quote. This produces the total accuracy quotes for liquid flow measurement of ± 0.13% and for gas flow measurement of ± 0.25%.

## Flow Measurement Traceability

To establish the realistic traceability described above, a test program must be devised so that:

(1) high confidence can be placed in the artifact package—the meters assembled and the specifics of the procedures, checkpoints, responses to anticipated anomalies, etc.;

(2) the data base produced is adequate to the task of clearly evaluating the significant components of the systems that participate; and

(3) the algorithm for processing the data producing the results is an unbiased and clear procedure that is adequate to this task.

Artifact confidence is established via calibration testing over an extended period of time for the kind of conditions that will be used in the round robin. This testing should occur in the initiating laboratory and it should establish a credible background data base for the units being tested. Specifically, high confidence can be attained both in meter performance and in facility operation by calibrating two (2) meters in series according to tightly specified conditions. This type of configuration is shown in Figure 24-3. Pretesting of these configurations gives ex-

pected values for the respective meter factors as well as for the relative performance of the meters, i.e., the ratio of their outputs.

Adequacy of the data base is established by specifying the number of repeat calibrations done for each flow rate and meter configuration. These results should produce sufficient data so that statistical significance can be generated to exhibit the quality of measurement performance: (1) how this varies for successive calibrations done for the same conditions over short periods of time, i.e., repeatability; and (2) how this varies from day to day for conditions that may vary slightly, i.e., reproducibility. It is recommended here that the data base be generated efficiently and for the expressed purpose of testing laboratory performance. To do this, a minimum number of flow rates are used and sufficient tests at each are done.

**An alternative approach might be to use numerous flow rates and minimal replications at each. However, this alternative approach tends to place an undesirable emphasis on meter characteristics as opposed to test laboratory characteristics.**

The algorithm for data processing should be well established. This attribute is achieved when it is (has been) used for a number of MAPs for other measurement systems, i.e., the procedures produced by W. J. Youden and co-workers [Ref. 19].

By testing in both configurations shown in Figure 24-3, the upstream data and the downstream data, individually, have the statistical independence requirement that is needed to apply the Youden procedure, etc. The SFC unit shown in Figure 24-3 is a "super flow conditioner" placed between the tandem meters [Refs. 15-17]. Here, it is intended to isolate the downstream meter from flow profile (or other anomalies) that might exist in the laboratory pipeline that connects to the upstream meter. Thus, the tandem meter configuration affords one the opportunity of generating data both without and with pipeflow profile effects, because

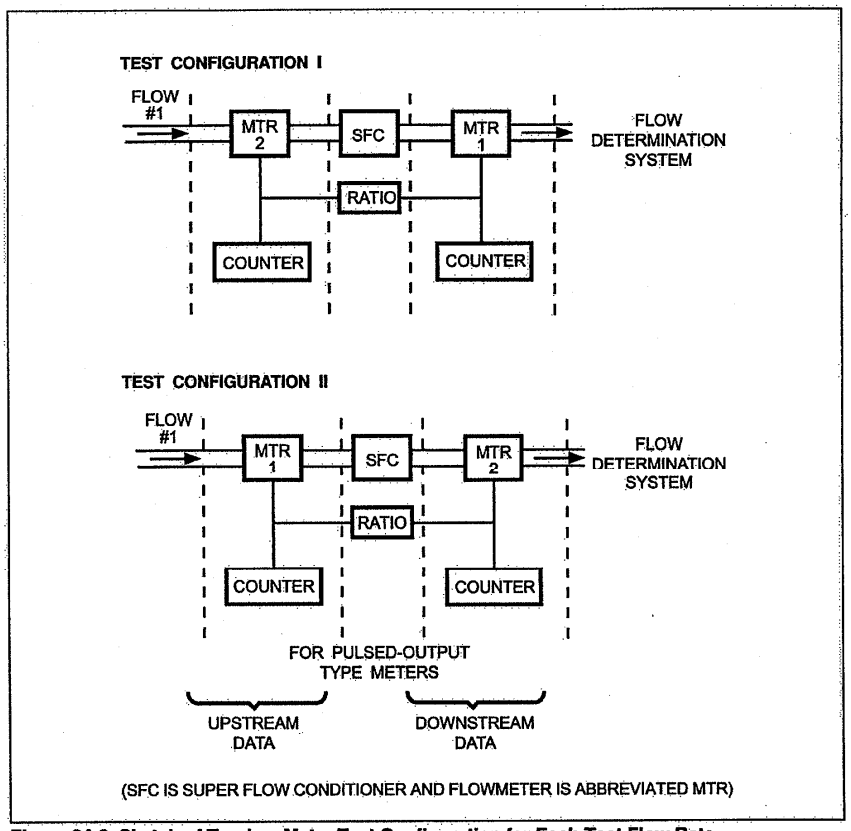


**Figure 24-3. Sketch of Tandem Meter Test Configuration for Each Test Flow Rate**

downstream meter and upstream meter performances can be analyzed separately. Comparisons can give unique global insights into laboratory pipeflow phenomena without having to measure these distributions.

The types of flowmeters for this type of laboratory testing should be selected according to the experiences of the participating laboratories. This consensus selection should produce the type of meter, the size, manufacture, associated instrumentation, etc. This selection process should be extended to include the fluid conditions, the flow rates, etc., as well as the tolerances to be used in arranging these.

The data generated via the round robin testing program is analyzed for each of the flow rates selected and for each of the meter positions. For each of these conditions, plots are produced of the respective meter performance characteristics (i.e., meter performance characteristics such as meter factor, discharge coefficient, etc. [Refs. 15-18]). Individual results, or averages thereof, can be plotted (see Figure 24-4). Each point represents the combined results for both meters when they were tested in each position in each laboratory.

The data processing procedures consist of determining median values for the respective sets of data for the meters. In this plot, thirteen (13) data points are shown, each representing one of the participating laboratories. Similar plots should be made for each of the other flow rates. Similar plots should be made for the meter results obtained when the meters were in the downstream position. By drawing horizontal and vertical lines through the median points for each meter, the plot is divided into four Cartesian quadrants, as shown by the dashed lines. The origin of this Cartesian system is, according to the available data, the best estimate of the true values of the meter factors for the two meters tested according to the specified conditions. In the northeast Cartesian quadrant, the data can be considered systematically inaccurate in that points are each higher than those of the origin. Similarly, in the southwest quadrant points are lower. Thus, the degree to which data is distributed in these quadrants is a measure of the systematic offsets prevailing in the laboratory data.

In the northwest and southeast quadrants the data can be considered inconsistent or random, in that one value is low while the other is high. Therefore, the degree to which the data is distributed in a northwest to southeast manner about the median intersection is a measure of the random variation in the data.

The preferred result, indicating good control, would be to find that the measurement of systematic distribution (northeast to southwest) is equal to the random

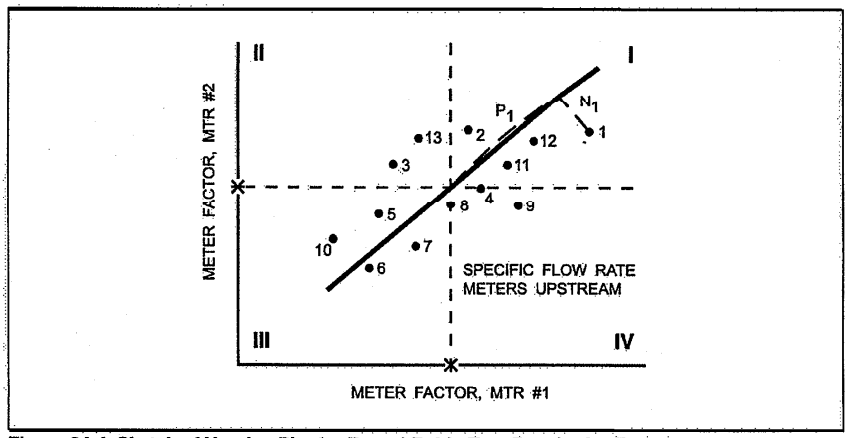


**Figure 24-4. Sketch of Youden Plot for Round Robin Test Results for Each Flow Rate and for Each Meter Position**

distribution (northwest to southeast) and that these measures are acceptably small. The respective levels of uncertainty can be quantified.

Where, as is usually the case, the two meters are identical, a procedure for quantifying the respective random and systematic levels of the data can be used as follows, [Refs. 15-17]. A line of slope + 1 is drawn through the intersection of medians on Figure 24-4. The data is then projected perpendicular and parallel to this diagonal line. The respective projections are then used to produce standard deviations:

$$\sigma_r = \left[\frac{1}{N-1}\sum_{i=1}^{N} N_i^2\right]^{1/2} \tag{24-6}$$

$$\sigma_s = \left[\frac{1}{N-1}\sum_{i=1}^{N} P_i^2\right]^{1/2} \tag{24-7}$$

where $N_i$ and $P_i$ are the normal and parallel components of the data projected to the diagonal line. The ratio of these quantities produces the degree of ellipticity of the data:

$$e = \frac{\sigma_s}{\sigma_r} \tag{24-8}$$

When this ratio is larger than unity, the interpretation is that systematic variations prevail among the labs; this is quantified by magnitude of $e$. Analogous conclusions can be drawn for $e < 1$.

Depending upon the results obtained for ellipticity, a number of reactions can occur. If $e$ is large and this is produced by one or more laboratories, then the reaction should be to examine the components of their flow measurement processes to find systematic causes, etc. If $e$ is small and this is produced by one or more laboratories, the reaction should be to examine the components of their processes with respect to their precision. If $e$ is near unity but the levels of uncertainty are considered too large, then the appropriate response would be for the labs responsible to search and repair the pertinent components' systematic and random errors.

When such search and repair efforts are completed, the round of tests should be repeated for the same conditions so that improvements can be quantified. Even when such search and repair efforts are not needed, repeat testing is needed to produce the continuous data record desired to substantiate that the realistic traceability established has not diminished in time.

## Conclusion

The standard philosophies for flow rate measurements have been presented. Uncertainty analyses are given for successive stages of flow rate measurement laboratory assessment. The techniques used for fluid flow rate calibration facilities have been described briefly. Nominal levels of performance have been given for typical facilities at NIST-Gaithersburg, MD.

The NIST flow rate measurement accuracy quotes of ± 0.13% for liquids and of ± 0.25% for air are described, where precisions are produced by the root-sum-square method and systematic errors are added to the random errors. An alternative way of combining systematic and random errors could be by root-sum-square. However, because systematic errors in flow laboratory assessments are generally estimated, it is felt that the more conservative method of combination is

preferred. The systematic portion of these quotes is estimated to be ± 0.1% on the basis of round robin tests.

Techniques for establishing and maintaining flow rate measurement traceability have been presented. A specific scheme has been described in some detail so that realistic data, produced on a continuing basis, can be generated so that a laboratory's entire flow rate measurement process can be assessed.

It is concluded that once these types of traceability chains are produced so that flow measurement laboratories are linked within and across national borders and boundaries, satisfactory fluid measurements can be achieved at specified levels. In this manner, the increasingly critical and costly measurements of valuable fluid resources and products can occur satisfactorily for the widely varying conditions and reasons for making flow rate measurements.

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## About the Author

Dr. George E. Mattingly has been at NIST since 1975 and is the leader of the NIST Fluid Flow Group. In this position, he is responsible for the maintenance and dissemination of the flow measurement standards that use water, air, and hydrocarbon liquids. Additionally, he is responsible for air speed measurements and liquid volume and density standards. In these capacities, he is involved in numerous committee activities—both national and international—to upgrade old or to generate new paper standards on these and related topics.

Dr. Mattingly is also involved in a wide range of fluid mechanics and flow measurement research projects. These include flowmeter installation effects; establishing realistic traceability for fluid meter calibration facilities; devising improved accuracies for fluid density and flow calibration systems; studying fluid-structure interaction phenomena; and characterizing and improving liquid metal atomization processes. Dr. Mattingly has authored or co-authored almost 100 publications or reports on a wide range of flow topics.